CLAIMS

What is claimed is:

1. In a system, a method of operation comprising:

receiving a first plurality of signals wirelessly transmitted by a plurality of signal sources, employing a plurality of sensors;

taking a first sample of the received signals sensed by the sensors;

constructing a first received signal vector based on the first sample, employing a first plurality of signal directional vectors; and

determining a first plurality of directions of arrival for the signals based at least in part on a relationship between the first received signal vector and the first plurality of signal directional vectors.

2. The method of claim 1, wherein

the plurality of signals comprise J signals wirelessly transmitted by J corresponding signal sources with center frequency f_0, the J signals traveling at speed c and impinging on the sensors from directions of arrival $\theta_1 \ldots \theta_J$;

said receiving comprises receiving the J signals employing N sensors with spacing d, where N is an integer greater than 1, and

said constructing of a first received signal comprises constructing a first received signal vector ($\mathbf{x}(t)$) given by

$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t)$$

where

$$\mathbf{x}(t) = [x_1(t), \ldots, x_J(t)]^T$$

$$\mathbf{A} = [\mathbf{a}(\theta_1), \ldots \mathbf{a}(\theta_J)]$$

$\mathbf{a}(\theta_j) = \left[1 \quad e^{-ikd\cos\theta_j} \quad . \quad . \quad e^{-i(N-1)kd\cos\theta_j}\right]^T$, $j = 1,...J$, are the signal directional vectors,

$\mathbf{s}(n) = [s_1(n),...,s_J(n)]^T$ are complex envelopes of outputs at the sensors, and

$k = 2\pi f_0 / c$.

3. The method of claim 2, wherein said determining of a first plurality of directions of arrival for the signals comprises determining $\theta_1 \ldots \theta_L$ based at least in part on $\mathbf{a}(\theta_i)$ for $i = 1 \ldots J$ intersecting with a subspace spanned by the first $\mathbf{x}(t)$.

4. The method of claim 3, wherein said determining of the first plurality of directions of arrival for the signals further comprises computing

a first coefficient $r_{11} = \|\mathbf{x}(t)\|$, and

a first orthonormal vector $\mathbf{q}_1 = \dfrac{\mathbf{x}(t)}{r_{11}}$.

5. The method of claim 4, wherein said determining of a first plurality of directions of arrival for the signals further comprises computing for $\mathbf{a}(\sim\theta_i)$

a second coefficient $r_{12} = \mathbf{q}_1^H \mathbf{a}(\sim\theta_i)$,

a second orthonormal vector $\mathbf{q}_2 = \mathbf{a}(\sim\theta_i) - r_{12}\mathbf{q}_1$, and

a third coefficient $r_{22} = \|\mathbf{q}_1^H \mathbf{a}(\sim\theta_i)\|$,

where $\sim\theta_i$ is a trial value for $\theta_1 \ldots \theta_J$.

6. The method of claim 5, wherein said determining of a first plurality of directions of arrival for the signals further comprises evaluating a function

$B(\theta) = \dfrac{1}{r_{22}}$ for $\sim \theta_i$, and determining whether the evaluation yields a peak value for the function.

7. The method of claim 6, wherein said determining of a first plurality of directions of arrival for the signals further comprises repeating said computing, evaluating and determining whether the evaluation yields a peak value for the function, for J or more $\mathbf{a}(\sim \theta_i)$, and setting J peak values as $\theta_1 \ldots \theta_J$.

8. The method of claim 1, wherein said determining of a first plurality of directions of arrival for the signals comprises determining the first plurality of directions of arrival based at least in part on the first plurality of signal directional vectors intersecting with a subspace spanned by the first received signal vector.

9. The method of claim 1, wherein the method further comprises

taking a second sample of the received signals sensed by the sensors;

constructing a second received signal vector based on the second sample, employing a second plurality of signal directional vectors; and

determining a second plurality of directions of arrival for the signals based at least in part on a relationship between the second received signal vector and the second plurality of signal directional vectors.

10. The method of claim 9, wherein the method further comprises determining a third plurality of directions of arrival based at least in part on corresponding averages of the first and second plurality of directions of arrival.

11. In a system, a method of operation comprising:

receiving a plurality of signals wireless transmitted by a plurality of signal sources, employing a plurality of sensors;

determining a first plurality of directions of arrival for a first plurality of multipaths of a first of the signals; and

obtaining the first received signal based at least in part on the determined first plurality of directions of arrival for the first plurality of multipaths of the first signal.

12. The method of claim 11, wherein

the method further comprises determining a second plurality of directions of arrival for the signals; and

said determining of the first plurality of directions of arrival for the first plurality of multipaths of the first signal comprises searching for the first plurality of directions of arrival for the first plurality of multipaths of the first signal in a direction range centered on the determined direction of arrival of the first signal.

13. The method of claim 11, wherein

the method further comprises determining a correlation matrix for the signals, and determining a plurality of eigenvectors of the correlation matrix corresponding to the signals; and

said determining of the second plurality of directions of arrivals for the signals, including the direction of arrival of the first signal, is performed based at least in part on the determined eigenvectors of the correlation matrix corresponding to the signals.

14. The method of claim 13, wherein said determining of the correlation matrix comprises averaging a plurality of sets of outer-products of a plurality of signal

plus noise vectors determined based on a plurality of corresponding snapshots of the signals sensed by the sensors.

15. The method of claim 11, wherein

said receiving of a plurality of signals comprises receiving J signals wirelessly transmitted by J signal sources, employing N sensors, where J and N are integers, each greater than 1;

the jth transmitted signal is modeled as $x_j(t) = s_j(t)e^{j(2\pi(2+\varphi_0))}$, $s(t)$ being a base band signal, and φ_0 being an initial phase; and

the received jth signal is given by $\mathbf{x}_j(t) = \sum_{l=1}^{L} R_{jl} e^{i2\pi(f_d \cos\theta_{jl} - f\tau_{jl})} s(t - \tau_{jl})$

where Rjl is the signal strength of the l'th multipath of the j'th signal,

$f_d Cos\theta_{jl}$ is a Doppler shift the l'th multipath of the j'th signal,

f is a carrier frequency,

$s()$ is a base band signal,

$\tau_{jl} = r_{jl}/c$ is a time delay of the l'th multipath of the j'th signal,

r_{jl} is a range of the l'th multipath of the j'th signal,

c is speed of Electromagnetic wave, and

θ_{jl} is the direction of arrival of the l'th multipath of the j'th signal.

16. The method of claim 15, wherein

a response vector at the N sensor for a signal impinging from an angle θ is given by $\mathbf{v}(\theta_{jl}) = [1 \quad e^{\frac{-i2\pi Cos\theta_{jl}}{\lambda}} \quad e^{\frac{i4\pi Cos\theta_{jl}}{\lambda}} \quad \ldots\ldots \quad e^{\frac{i2\pi(N-1)Cos\theta_{jl}}{\lambda}}]^T$; and

a baseband signal vector corresponding to the l'th multipath of the j'th signal impinging from an angle θ_{jl} is given by

$$\mathbf{x}_j(t) = \sum_{l=1}^{L} \mathbf{v}(\theta_{jl}) R_{jl} e^{i2\pi(f_d cos\theta_{jl} - f\tau_{jl})} s(t - \tau_{jl}).$$

17. The method of claim 16, wherein said searching comprises computing for a search vector $\{\mathbf{v}(\theta_{jk_l}), \mathbf{v}(\theta_{jk_2}), \ldots, \mathbf{v}(\theta_{jk_L})\}$, θ_{jk_l} being a search angle,

$$r_{11} = \| \mathbf{v}(\theta_{jk_1}) \|_2 \text{ and}$$

$$\mathbf{q}_1 = \frac{\mathbf{v}(\theta_{jk_1})}{r_{11}}$$

$\|.\|_2$ is the 2-norm of the vector.

18. The method of claim 17, wherein said searching further comprises computing

$$r_{il} = \mathbf{q}_i^H \mathbf{v}(\theta_{jk_l}); \qquad 1 \le i \le l-1; \qquad l = 2,\ldots,L+1$$

$$r_{ll} = \| \mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il}\mathbf{q}_i \|_2, \quad l = 2,\ldots,L+1, \text{ and}$$

$$\mathbf{q}_l = [\mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il}\mathbf{q}_i] / r_{ll}, \quad l = 2,\ldots,L+1.$$

19. The method of claim 18, wherein said searching further comprises determining whether a function $B(\Theta_j) = \frac{1}{r_{L+1,L+1}}$ yields a peak value, and if so, setting $\Theta_j = \{\theta_{j1}, \ldots, \theta_{jL}\}$ as the first directions of arrival of the first plurality of multipaths of the first signal.

20. The method of claim 11, wherein said obtaining of the first received signal comprises obtaining $z(t)$ based on the determined directions of arrival of L-multipaths of the first received signal as follows

$$z(t) = \sum_{l=1}^{L}\sum_{n=1}^{N} x_n w_{nl} \quad \text{where } w_{nl} = e^{-ikd(n-1)\cos\hat{\theta}_{jl}}$$

21. An apparatus comprising:

storage medium having stored therein programming instructions designed to enable the apparatus to

construct a first received signal vector employing a first plurality of signal directional vectors; based at least in part on a first sample of a plurality of received signals wirelessly transmitted by a plurality of signal sources, received employing a plurality of sensors; and

determine a first plurality of directions of arrival for the signals based at least in part on a relationship between the first received signal vector and the first plurality of signal directional vectors; and

at least one processor coupled to the storage medium to execute the programming instructions.

22. The apparatus of claim 21, wherein

the plurality of signals comprise J signals wirelessly transmitted by J corresponding signal sources with center frequency f_0, the J signals traveling at speed c and impinging on the sensors from directions of arrival $\theta_1 \ldots \theta_J$;

the J signals are received employing N sensors with spacing d, where N is an integer greater than 1, and

the programming instructions are designed to perform said constructing of a first received signal by constructing a first received signal vector ($\mathbf{x}(t)$) given by

$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t)$$

where

$$\mathbf{x}(t) = [x_1(t), \ldots, x_J(t)]^T$$

$$\mathbf{A} = [\mathbf{a}(\theta_1), \ldots \mathbf{a}(\theta_J)]$$

$\mathbf{a}(\theta_j) = \left[1 \quad e^{-ikd\cos\theta_j} \quad . \quad . \quad e^{-i(N-1)kd\cos\theta_j}\right]^T$, $j = 1,\ldots J$, are the signal directional vectors,

$\mathbf{s}(n) = \left[s_1(n),\ldots,s_J(n)\right]^T$ are complex envelopes of outputs at the sensors, and

$k = 2\pi f_0 / c$.

23. The apparatus of claim 22, wherein the programming instructions are designed to perform said determining of a first plurality of directions of arrival for the signals by determining $\theta_1 \ldots \theta_L$ based at least in part on $\mathbf{a}(\theta_i)$ for $i = 1 \ldots J$ intersecting with a subspace spanned by the first $\mathbf{x}(t)$.

24. The apparatus of claim 23, wherein the programming instructions are further designed to perform as part of said determining, computing of

a first coefficient $r_{11} = \|\mathbf{x}(t)\|$, and

a first orthonormal vector $\mathbf{q}_1 = \dfrac{\mathbf{x}(t)}{r_{11}}$.

25. The apparatus of claim 24, wherein the programming instructions are designed to perform as part of said determining, computing for $\mathbf{a}(\sim\theta_i)$

a second coefficient $r_{12} = \mathbf{q}_1^H \mathbf{a}(\sim\theta_i)$,

a second orthonormal vector $\mathbf{q}_2 = \mathbf{a}(\sim\theta_i) - r_{12}\mathbf{q}_1$, and

a third coefficient $r_{22} = \|\mathbf{q}_1^H \mathbf{a}(\sim\theta_i)\|$,

where $\sim\theta_i$ is a trial value for $\theta_1 \ldots \theta_J$.

26. The apparatus of claim 25, wherein the programming instructions are designed to perform as part of said determining, evaluation of a function

$B(\theta) = \frac{1}{r_{22}}$ for $\sim\theta_i$, and determination of whether the evaluation yields a peak value for the function.

27. The apparatus claim 26, wherein the programming instructions are designed to perform as part of said determining, repeating of said computing, evaluation and determination of whether the evaluation yields a peak value for the function, for J or more $\mathbf{a}(\sim\theta_i)$, and setting of J peak values as $\theta_1 \ldots \theta_J$.

28. The apparatus of claim 21, wherein the programming instructions are designed to perform as part of said determining, determination of the first plurality of directions of arrival based at least in part on the first plurality of signal directional vectors intersecting with a subspace spanned by the first received signal vector.

29. The apparatus of claim 21, wherein the programming instructions are designed to perform

construction of a second received signal vector based on the second sample, employing a second plurality of signal directional vectors, based at least in part on a second sample of the received signals sensed by the sensors; and

determination of a second plurality of directions of arrival for the signals based at least in part on a relationship between the second received signal vector and the second plurality of signal directional vectors.

30. The apparatus of claim 29, wherein the programming instructions are further designed to enable the apparatus to determine a third plurality of directions of arrival based at least in part on corresponding averages of the first and second plurality of directions of arrival.

31. An apparatus comprising:

storage medium having a plurality of programming instructions designed to enable the apparatus to

determine a first plurality of directions of arrival for a first plurality of multipaths of a first of a plurality of signals wireless transmitted by a plurality of signal sources, and received employing a plurality of sensors, and

obtain the first received signal based at least in part on the determined first plurality of directions of arrival for the first plurality of multipaths of the first signal; and

at least one processor coupled to the storage medium to execute the programming instructions.

32. The apparatus of claim 31, wherein

the programming instructions are further designed to enable the apparatus to determine a second plurality of directions of arrival for the signals; and

the programming instructions are designed to perform said determining of the first plurality of directions of arrival for the first plurality of multipaths of the first signal by searching for the first plurality of directions of arrival for the first plurality of multipaths of the first signal in a direction range centered on the determined direction of arrival of the first signal.

33. The apparatus of claim 31, wherein

the programming instructions are further designed to enable the apparatus to determine a correlation matrix for the signals, and determine a plurality of eigenvectors of the correlation matrix corresponding to the signals; and

the programming instructions are designed to perform said determining of the second plurality of directions of arrivals for the signals, including the direction of arrival of the first signal, based at least in part on the determined eigenvectors of the correlation matrix corresponding to the signals.

34. The apparatus of claim 33, wherein the programming instructions are designed to perform said determining of the correlation matrix by averaging a plurality of sets of outer-products of a plurality of signal plus noise vectors determined based on a plurality of corresponding snapshots of the signals sensed by the sensors.

35. The apparatus of claim 31, wherein

said receiving of a plurality of signals comprises receiving *J* signals wirelessly transmitted by *J* signal sources, employing N sensors, where *J* and N are integers, each greater than 1;

the *j*th transmitted signal is modeled as $x_j(t) = s_j(t)e^{j(2\pi(2+\varphi_0))}$, $s(t)$ being a base band signal, and φ_0 being an initial phase; and

the received *j*th signal is given by $\mathbf{x}_j(t) = \sum_{l=1}^{L} R_{jl} e^{i2\pi(f_d \cos\theta_{jl} - f\tau_{jl})} s(t-\tau_{jl})$

where *Rjl* is the signal strength of the *l*'th multipath of the *j*'th signal,

$f_d Cos\theta_{jl}$ is a Doppler shift the *l*'th multipath of the *j*'th signal,

f is a carrier frequency,

$s()$ is a base band signal,

$\tau_{jl} = r_{jl}/c$ is a time delay of the *l*'th multipath of the *j*'th signal,

r_{jl} is a range of the *l*'th multipath of the *j*'th signal,

c is speed of Electromagnetic wave, and

θ_{jl} is the direction of arrival of the *l*'th multipath of the *j*'th signal.

36. The apparatus of claim 35, wherein

a response vector at the N sensor for a signal impinging from an angle θ is given by $\mathbf{v}(\theta_{jl}) = [\, 1 \quad e^{\frac{-i2\pi Cos\theta_{jl}}{\lambda}} \quad e^{\frac{i4\pi Cos\theta_{jl}}{\lambda}} \quad \ldots\ldots \quad e^{\frac{i2\pi(N-1)Cos\theta_{jl}}{\lambda}} \,]^T$; and

a baseband signal vector corresponding to the l'th multipath of the j'th signal impinging from an angle θ_{jl} is given by

$$\mathbf{x}_j(t) = \sum_{l=1}^{L} \mathbf{v}(\theta_{jl}) R_{jl} e^{i2\pi(f_d cos\theta_{jl} - ft_{jl})} s(t-\tau_{jl}).$$

37. The apparatus of claim 36, wherein the programming instructions are designed to perform as part of said searching, computation for a search vector $\{\mathbf{v}(\theta_{jk_l}), \mathbf{v}(\theta_{jk_2}), \ldots, \mathbf{v}(\theta_{jk_L})\}$, θ_{jk_l} being a search angle,

$$r_{11} = \| \mathbf{v}(\theta_{jk_1}) \|_2 \text{ and}$$

$$\mathbf{q}_1 = \frac{\mathbf{v}(\theta_{jk_1})}{r_{11}}$$

$\|\cdot\|_2$ is the 2-norm of the vector.

38. The apparatus of claim 37, wherein the programming instructions are designed to perform as part of said searching, computation of

$$r_{il} = \mathbf{q}_i^H \mathbf{v}(\theta_{jk_l}); \qquad 1 \le i \le l-1; \qquad l = 2,\ldots,L+1$$

$$r_{ll} = \| \mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il}\mathbf{q}_i \|_2, \quad l = 2,\ldots,L+1, \text{ and}$$

$$\mathbf{q}_l = [\mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il}\mathbf{q}_i] / r_{ll}, \quad l = 2,\ldots,L+1.$$

39. The apparatus of claim 38, wherein the programming instructions are designed to perform as part of said searching, determination of whether a

function $B(\Theta_j) = \frac{1}{r_{L+1,L+1}}$ yields a peak value, and if so, set $\Theta_j = \{\theta_{j1}, \ldots, \theta_{jL}\}$ as the first directions of arrival of the first plurality of multipaths of the first signal.

40. The apparatus of claim 31, wherein the programming instructions are designed to perform said obtaining of the first received signal by obtaining $z(t)$ based on the determined directions of arrival of *L*-multipaths of the first received signal as follows

$$z(t) = \sum_{l=1}^{L}\sum_{n=1}^{N} x_n w_{nl} \quad \text{where } w_{nl} = e^{-ikd(n-1)\cos\hat{\theta}_{jl}}$$

41. A system comprising:

a plurality of antennas to receive a plurality of signals wirelessly transmitted by a plurality of signal sources;

a RF unit coupled to the antennas to down convert the received signals; and

a direction of arrival estimation unit coupled to the RF unit, to

construct a first received signal vector employing a first plurality of signal directional vectors; based at least in part on a first sample of the received signals; and

determine a first plurality of directions of arrival for the signals based at least in part on a relationship between the first received signal vector and the first plurality of signal directional vectors.

42. The system of claim 41, wherein the direction of arrival estimation unit performs as part of said determination, determination of the first plurality of

directions of arrival based at least in part on the first plurality of signal directional vectors intersecting with a subspace spanned by the first received signal vector.

43. The system of claim 41, wherein the direction of arrival estimation unit further

constructs a second received signal vector employing a second plurality of signal directional vectors, based at least in part on a second sample of the received signals; and

determines a second plurality of directions of arrival for the signals based at least in part on a relationship between the second received signal vector and the second plurality of signal directional vectors.

44. The apparatus of claim 43, wherein the direction of arrival estimation unit further determines a third plurality of directions of arrival based at least in part on corresponding averages of the first and second plurality of directions of arrival.

45. A system comprising:

a plurality of antennas to receive a plurality of signals wirelessly transmitted by a plurality of signal sources;

a RF unit coupled to the antennas to down convert the received signals; and

a direction of arrival estimation unit coupled to the RF unit, to

determine a first plurality of directions of arrival for a first plurality of

multipaths of a first of a plurality of received signals wireless transmitted by a plurality of signal sources, and

obtain the first received signal based at least in part on the determined first plurality of directions of arrival for the first plurality of multipaths of the first signal.

46. The system of claim 45, wherein the direction of arrival estimation unit further

determines a second plurality of directions of arrival for the signals; and

determines the first plurality of directions of arrival for the first plurality of multipaths of the first signal by searching for the first plurality of directions of arrival for the first plurality of multipaths of the first signal in a direction range centered on the determined direction of arrival of the first signal.

47. The system of claim 45, wherein the direction of arrival estimation unit further

determines a correlation matrix for the signals, and determines a plurality of eigenvectors of the correlation matrix corresponding to the signals; and

determines the second plurality of directions of arrivals for the signals, including the direction of arrival of the first signal, based at least in part on the determined eigenvectors of the correlation matrix corresponding to the signals.

48. The system of claim 47, wherein the direction of arrival estimation unit determines the correlation matrix by averaging a plurality of sets of outer-products of a plurality of signal plus noise vectors determined based on a plurality of corresponding snapshots of the received signals.

49. An article of manufacture comprising

a machine readable medium having stored therein a plurality of programming instructions designed to enable an apparatus to be able to

construct a first received signal vector employing a first plurality of signal directional vectors; based at least in part on a first sample of a plurality of received signals wirelessly transmitted by a plurality of sources; and

determine a first plurality of directions of arrival for the signals based at least in part on a relationship between the first received signal vector and the first plurality of signal directional vectors.

50. The article of claim 49, wherein the programming instructions are designed to perform as part of said determination, determination of the first plurality of directions of arrival based at least in part on the first plurality of signal directional vectors intersecting with a subspace spanned by the first received signal vector.

51. An article of manufacture, comprising

a machine readable medium having stored therein a plurality of programming instructions designed to enable an apparatus to

determine a first plurality of directions of arrival for a first plurality of multipaths of a first of a plurality of received signals wireless transmitted by a plurality of signal sources, and

obtain the first received signal based at least in part on the determined first plurality of directions of arrival for the first plurality of multipaths of the first signal.

52. The article of claim 51, wherein the programming instructions are further designed to enable the apparatus to

determine a second plurality of directions of arrival for the signals; and

determine the first plurality of directions of arrival for the first plurality of multipaths of the first signal by searching for the first plurality of directions of arrival for the first plurality of multipaths of the first signal in a direction range centered on the determined direction of arrival of the first signal.